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A Unique Relationship Determining Strength of Silty/Clayey Soils – Portland Cement Mixes

Nilo Cesar Consoli[1], Pedro Miguel Vaz Ferreira[2], Chao-Sheng Tang[3], Sérgio Filipe Veloso Marques[4], Lucas Festugato[5] and Marina Bellaver Corte[6]

ABSTRACT: This technical note advances the understanding of the key parameters controlling unconfined compressive strength (q_u) of artificially cemented silty/clayey soils by considering distinct moisture contents, distinct specimen porosities (η), different Portland cement contents and any curing time periods. The q_u values of the specimens moulded for each curing period were normalized (i.e. divided) by the q_u attained by a specimen with a specific porosity/cement ratio. A unique relationship was found, establishing the relationship between strength for artificially cemented silty/clayey soils considering all porosities, Portland cement amounts, moisture contents and curing periods studied. From a practical viewpoint, this means that, at limit, carrying out only one unconfined compression test with a silty/clayey soil specimen, moulded with a specific Portland cement amount, a specific porosity and moisture content and cured for a given time period, allows the determination of a general relationship equation that controls the strength for an entire range of porosities and cement contents, reducing considerably the amount of moulded specimens and reducing projects development cost and time.

Keywords: Normalization, porosity, Portland cement, strength, fine grained soils, porosity/cement ratio.

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INTRODUCTION

In roads and other shallow constructions, Portland cement is often used to improve soils, for example to make them better suited as subgrades and foundation backfill (e.g. Ingles and Metcalf 1972; Thomé *et al.* 2005; Onyejekwe and Ghataora 2015). Previous studies of silty/clayey soils–cement (Consoli *et al.* 2007, 2011, 2012, Marques *et al.* 2014) have shown that their behaviour is complex, and affected by many factors, such as the size and shape of the sand, the amount of Portland cement, the porosity and curing time period. Consoli *et al.* (2007) were the first to establish a unique dosage methodology based on rational criteria where the porosity/cement ratio plays a fundamental role in the assessment of a target unconfined compressive strength. In the present research, the possibility of taking advantage of normalizing the results was searched using the porosity/cement ratio. This study shows the influence of the amount of Portland cement and the porosity on the unconfined compressive strength (q_u) of seven different silty/clayey soils: London clay, Paraguayan dispersive clay, Portugal silty sand, Botucatu clayey sand, Nova Santa Rita organic soft soil, Cachoeirinha red silty clay and Pantano Grande silt. A normalisation was searched by dividing every single strength value (for each silty/clayey soil studied) by the q_u attained at a specific porosity/cement ratio and a unique power function was obtained quantifying the influence of amounts of Portland cement, porosity and curing time in the assessment of q_u of silty/clayey soil–cement mixtures. From a practical viewpoint, this means that carrying out only one unconfined compression test with a specimen of the studied silty/clayed soil, moulded with Portland cement and cured for any time period, allows the determination of a unique relationship that controls the strength of an entire range of porosities and cement contents. Following, it was possible to generalize such relationship to fine grained materials (gold tailings and coal fly ash – grinded and not grinded) treated with Portland cement.

EXPERIMENTAL PROGRAM

The experimental program has been carried out in two parts. First, the properties of the several silty/clayey soils were characterized. Then a number of unconfined compression tests were carried out for silty/clayey soils - Portland cement blends considering different amounts of cement, up to four dry unit weights varying from low to high values, up to three moisture contents and distinct curing time periods (from 3 to 28 days of curing).

Materials

Seven different silty/clayey soils were used in present research: London clay, Paraguayan dispersive clay, Portugal silty sand, Botucatu clayey sand, Nova Santa Rita organic soft soil, Cachoeirinha red silty clay and Pantano Grande silt. The soils characterization test results are shown in Table 1. As can be seen in Table 1, silty/clayey soils with distinct characteristics were considered, such as high plasticity and low plasticity soils, silty/clayey sands and even an organic soil.

Early strength Portland cement was used as the cementing agent. The standard curing time period adopted was 7 days, (however eventually 3 and 28 days were also used). The specific gravity of the Portland cement grains was considered to be 3.15.

Tap water was used for the characterization tests, as well as for moulding specimens for the mechanical tests.

Methods

Moulding and Curing of Specimens

For the unconfined compression tests, cylindrical specimens 50 mm in diameter and 100 mm in height were used. A target dry unit weight for a given specimen was then established through the dry mass of silty-clayey soil-Portland cement divided by the total volume of the specimen. In order to keep the dry unit weight of the specimens constant with increasing Portland cement content, a small portion of the clay was replaced by Portland cement. Porosity (η) is defined as the ratio of voids (in volume) over the total volume of the specimen. As shown in Eq. (1), porosity (η) is a function of dry unit weight (γ_d) of the blend and Portland cement content (C). Each blend (soil and Portland cement) has a unit weight of grains (γs_s and γs_c), which also needs to be considered for calculating porosity.

$$\eta = 100 - 100\left\{\left[\frac{\gamma_d}{1+\left(\frac{C}{100}\right)}\right]\left[\frac{1}{\gamma s_s}+\frac{\frac{C}{100}}{\gamma s_c}\right]\right\} \quad (1)$$

After each silty/clayey soil, early strength Portland cement and water were weighed, every soil and cement were mixed until the mixture acquired a uniform consistency. The water was then added, continuing the mixing process until a homogeneous paste was created. The amount of cement for each mixture was calculated based on the mass of dry soil. The specimen was then statically compacted in three layers inside a cylindrical split mould, which was lubricated, so that each layer reached the specified dry unit weight. The top of each layer was slightly scarified. After the moulding process, the specimen was immediately extracted from the split mould and its weight, diameter and height measured with accuracies of about 0.01g and 0.1mm, respectively. The samples were then placed inside plastic bags to avoid significant variations of moisture content. They were cured in a humid room at 23º±2ºC and relative humidity above 95%. The samples were considered suitable for testing if they met the following tolerances: *Dry unit weight* (γ_d): degree of compaction between 99% and 101% (the degree of compaction being defined as the value obtained in the moulding process divided by the target value of γ_d).

Unconfined Compression Tests

Unconfined compression tests have been systematically used in most experimental programs reported in the literature, in order to verify the effectiveness of the stabilization with cement or to access the importance of influencing factors on the strength of cemented soils. One of the reasons for this is the accumulated experience with this kind of test for concrete. The tests usually followed the Brazilian standard NBR 5739 (ABNT 2010), which is similar to the ASTM C39 (ASTM 2010), being simple and fast, while reliable and cheap.

An automatic loading machine with maximum capacity of 50kN and a proving ring with capacity of 10kN and resolution of 0.005kN were used for the unconfined compression tests. Before carrying out testing, the specimens were submerged in a water tank for 24 hours for saturation to minimize suction (Consoli *et al*. 2012). The water temperature was controlled and maintained at 23 ± 2ºC. Immediately before the test, the specimens were removed from the tank and dried superficially with an absorbent cloth. Then, the unconfined compression test was carried out and the maximum load recorded. Because of the typical scatter of data for unconfined compression tests, for each point, three specimens were tested. The testing program was chosen in such a way as to evaluate, separately, the influences of the Portland cement content, the dry unit weight and the porosity/cement ratio. The moulding data (cement percentages, dry unit weight, moisture content and curing time periods) of all tested silty/clayey soil is presented in Table 2.

RESULTS

Effect of the Portland Cement Content, Porosity and Porosity/Cement Ratio on Compressive Strength

The unconfined compressive strength (q_u) variation with porosity (η) for the Pantano Grande silt treated with 3, 5, 7 and 9 % of early strength Portland cement, water content of 20% and a 7 days curing period is shown in Fig. 1a. In the figure it can be seen that increasing porosity (η) and reducing Portland cement content ends up reducing q_u. Exponential functions fit well to the relations of $q_u - \eta$ considering the distinct Portland cement contents. Fig. 1b shows q_u variation with η considering C=7%, water contents of 17%, 20% and 23% and 7 days as curing period. It can be seen in such results that, for the studied range of moisture content, increasing moisture content causes a rise in q_u, for all the porosity ranges studied. The other six silty/clayey soils studied (London clay, Paraguayan dispersive clay, Portugal silty sand, Botucatu clayey sand, Nova Santa Rita organic soft clay and Cachoeirinha red silty clay) were also treated with early strength Portland cement and studied considering curing periods varying from 3 to 28 days; these samples presented similar behavioural trends.

Figure 2 presents q_u as a function of the adjusted porosity/cement ratio $\eta/(C_{iv})^{0.28}$ [expressed as porosity (η) divided by the volumetric cement content (C_{iv}), the latter expressed as a percentage of cement volume regarding total volume (Consoli *et al.* 2007)] for all silty/clayey soils treated with early strength Portland cement studied herein, as well as for all moisture contents and curing periods studied. The exponent value 0.28 was found to be the best-fit exponent for all silty/clayey soils studied herein. Previous empirical studies on clayey sand (Consoli *et al.* 2007), silty-clay and sandy-clay (Consoli *et al.* 2011), and silty sand (Rios 2011, Consoli *et al.* 2012) have shown that the exponent might slightly vary from 0.21 to 0.35, having an average value of 0.28 (adopted as the representative value in present research).

Unique Relationship Establishing Strength

According to Consoli *et al.* (2007), the unconfined compressive strength of Portland cement treated silty-clayey soils follow equations such as Eq. (2).

$$q_u = A\left[\frac{\eta}{(C_{iv})^D}\right]^{-B} \tag{2}$$

in which *A*, *B* and *D* are scalars.

Diambra *et al.* (2016) applied the principles of the critical state soil mechanics and a mixture-modelling framework to predict compressive strength of cemented soils. These authors developed a theoretical model able to provide a direct connection between the individual material (soil and cement grains) properties and the empirical coefficients of Eq. (2), providing a physical meaning to the fitting data process results. According to Diambra *et al.* (2016) studies, the theoretical development yields in Eq. (3) for the unconfined compression strength

$$q_u = K\left[\frac{\eta}{(C_{iv})^{1/a}}\right]^{-a} \tag{3}$$

in which *K* and *a* are scalars. Additionally, *K* is a function of parameters linked to soil (e.g. critical state strength ratio – M for the soil) and Portland cement (e.g. unconfined compressive strength of the cement phase, ratio between the unconfined compressive and tensile strengths of the cement phase).

Comparing Eqs. (2) (empirical) and (3) (theoretical), it can be observed that $B_{theoretical}=a$ and $D_{theoretical}=1/a$ are related and *A* is a scalar linked to both soil and cement characteristics.

Dividing Eq. (2) by a particular value of strength, corresponding to a given value of $\eta/(C_{iv})^D = \nabla$ within the studied range, and assuming $D_{theoretical}=D=0.28$ (but $D_{theoretical}=1/a$, then $a=3.57$ and so $B_{theoretical}=3.57$) leads to Eq. (4).

$$\frac{q_u}{q_{u(\text{for a particular } \nabla)}} = \frac{A\left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-B}}{A[\nabla]^{-B}} \tag{4}$$

In a most suitably form, Eq. (4) is converted to Eq. (5).

$$\frac{q_u}{q_{u(\,for\,a\,particular\,\nabla)}} = [\nabla]^B \left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-B} \qquad (5)$$

For the case examined here, $[\eta/(C_{iv})^{0.28}] = \nabla = 30$ was used for the seven silty-clayey soils – Portland cement blends (a total of 342 specimens' strength results) studied herein (the q_u for normalization for each blend can be found in Table 3), leading to Eq. (6) (see Fig. 3).

$$\frac{q_u}{q_{u(\,for\,particular\,\nabla=30)}} = 486{,}000 \left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-3.85} \qquad (6)$$

Eq. (6) coefficient of determination (R^2) is high at about 0.91. The particular value of q_u at $[\eta/(C_{iv})^{0.28}=30]$ was chosen in present case once $\nabla = 30$ exists for all silty-clayey soils – Portland cement results tested. Comparing Eqs. (5) and (6), it can be seen that $\nabla^B = 486{,}000$, for $\nabla=30$ and B=3.85. It can be observed that B=3.85 is quite similar to $B_{theoretical}$=3.57. So, the adoption of B=3.85 has a theoretical mainstay.

So, in order to generalize the findings, inserting B=3.85 in Eq. (5) it turns into Eq. (7), which is valid for any ∇ inside the studied range. So, one can pick the most convenient $[\eta/(C_{iv})^{0.28}] = \nabla$.

$$\frac{q_u}{q_{u(\,for\,a\,particular\,\nabla)}} = [\nabla]^{3.85} \left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-3.85} \qquad (7)$$

Eq. (7) provides an important practical contribution. It allows the strength performance for a specific blend of silty/clayey soils and cement cured for a specific period (for a given range of cement contents and porosities) to be obtained by performing only one test. If possible, this test should comprise three identical specimens to obtain a good representativity for $q_{u(for\ particular\ \nabla)}$. Based on the experience obtained with the existing data, it is suggested the use of ∇ values nearby 30.

Looking for a possible generalisation of the developed normalization to other fine-grained materials treated with early strength Portland cement, Eq. (7) will be used to check its potential for gold tailings (a residue from milling rock for gold extraction) and coal fly ash (a residue of coal burning in a thermal power station). The materials physical properties are shown in Table 1, details of moulding and curing in Table 2 and normalization data in Table 3.

Gold tailings – cement data used was taken from specimens with $\nabla = \eta/(C_{iv})^{0.28} = 29.0$ and $q_{u(\text{for } \nabla=29.0)}$=1817.4 kPa (see Fig. 4(a) and Table 3 for details). Substituting the values obtained above in Eq. (7), Eq. (8) is obtained.

$$q_u(kPa) = 7.77x10^8 \left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-3.85} \tag{8}$$

Altering $\eta/(C_{iv})^{0.28}$ from 26.0 to 48.0 in Eq. (8), a curve is drawn in Fig. 4(a) together with lab-testing data points. It can be observed in Fig. 4(a) that the curve obtained using Eq. (8) is a fair representation (R^2=0.97) of lab testing data.

Coal fly ash – cement specimen used for obtaining the curve with $\nabla = \eta/(C_{iv})^{0.28} = 31.6$ and $q_{u(\text{for } \nabla=31.6)}$=2983.0 kPa [see Fig. 4(b) and Table 3 for details]. Replacing the values acquired above in Eq. (7), Eq. (9) is obtained.

$$q_u(kPa) = 2.32x10^9 \left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-3.85} \tag{9}$$

Varying $\eta/(C_{iv})^{0.28}$ from 28.0 to 61.0 in Eq. (9), a curve is drawn in Fig. 4(b) together with lab-testing data points. It can be observed in Fig. 4 that the curve obtained using Eq. (9) is a reasonable representation (R^2=0.89) of lab testing data. It is possible to observe that the shape of the draw curve is quite similar to the trend shown by the lab points.

Finally, it is important to state that the unique relationship establishing strength developed herein was determined and validated for blends considering fine grain soils with distinct characteristics (grain size distribution, plasticity index), early strength Portland cement, distinct moisture contents, and curing periods of up to 28 days (the latter restricted to the dispersive soil), performing well in all studied conditions.

CONCLUSIONS

From the data presented in this technical note the following conclusions can be drawn:

- Taking advantage of the fact that an exclusive correlation shape expresses q_u versus adjusted porosity/cement ratio, as well as of a normalization of the data by dividing the values of q_u by the value of strength of a specific $\eta/(C_{iv})^{0.28}$ [see Eq. (7)] for all fine-grained materials–cement mixtures studied herein considering distinct moisture contents, porosities, amounts of cement and curing periods considered, it was possible to establish and validate a unique relationship determining strength of fine-grained soils with distinct characteristics (grain size distribution, plasticity index), molding moisture contents and distinct curing periods up to 28 days (the latter is restricted to the dispersive soil), performing well in all studied conditions.

- From a practical viewpoint, this means that carrying out only a limited number of unconfined compression tests (in reality three identical specimens, in order to have a better representation of the average q_u value) with a specimen of a specific fine-grained soil-cement blend considering particular molding moisture content, curing period, porosity and Portland cement content, allows the establishment of a strength relationship considering a whole range of cement amounts and porosities, reducing dramatically the amount of moulded specimens and reducing projects development cost and time.

ACKNOWLEDGEMENTS

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NOTATION

C	*cement content (expressed in relation to mass of dry soil)*
C_{iv}	*volumetric cement content (expressed in relation to the total specimen volume)*
D_{50}	*mean effective diameter*
q_u	*unconfined compressive strength*
R^2	*coefficient of determination*
η	*porosity*
η/C_{iv}	*porosity/cement ratio*
γ_d	*dry unit weight*
γs_c	unit weight of cement grains
γs_s	unit weight of soil grains
w	*moisture content*

TABLES

Table 1. Physical properties of the soil samples

Soil Type	London clay	Dispersive clay	Botucatu residual soil	Organic soft clay	Red silty clay	Silt	Gold Tailings	Coal fly ash
Liquid limit (%)	78	43	23	74	43	39	-	-
Plastic limit (%)	30	19	13	33	22	34	-	-
Plastic index (%)	48	24	10	41	21	5	Non-plastic	Non-plastic
Specific gravity	2.75	2.74	2.63	2.60	2.67	2.64	2.86	2.16
Coarse sand (2.0mm < diameter < 4.75mm) (%)	-	-	-	-	-	-	-	1.0
Medium sand (0.425mm < diameter < 2.0mm) (%)	-	-	6.0	-	4.0	-	-	4.0
Fine sand (0.075mm < diameter < 0.425mm) (%)	2.0	7.0	51	1.0	30.0	1.5	28.0	15.0
Silt (0.002 mm < diameter < 0.075 mm) (%)	48.0	59.0	38	27.0	26.0	65.5	71.0	78.0
Clay (diameter < 0.002 mm) (%)	50.0	34.0	5.0	72.0	40.0	33.0	1.0	2.0
Mean particle diameter, D_{50} (mm)	0.002	0.005	0.16	0.001	0.012	0.006	0.06	0.015
USCS class	CH	CL	SC	OH	CL	ML	ML	ML

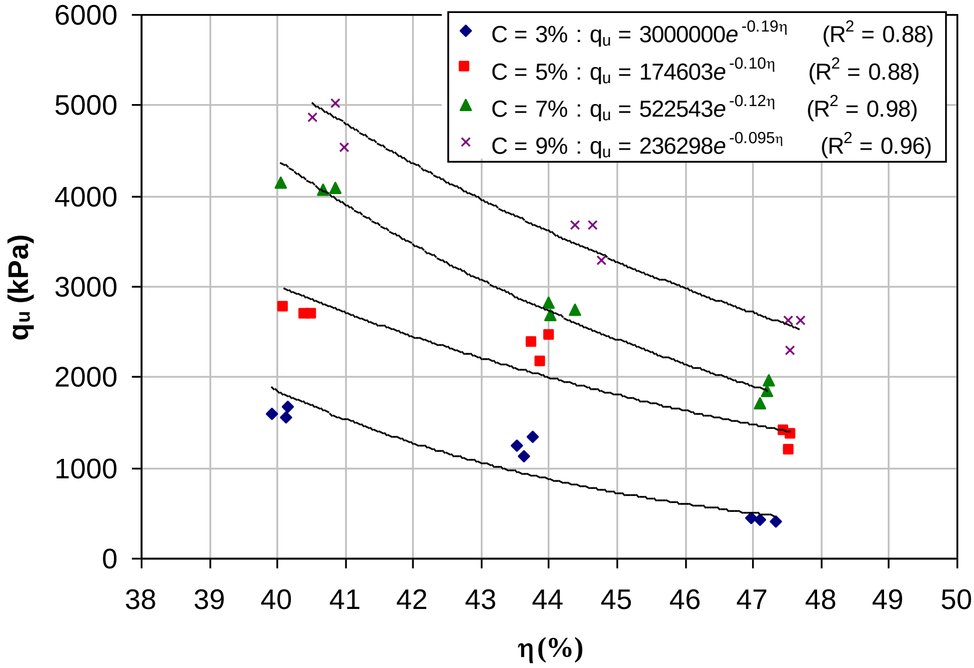
Table 2. Details of moulding and curing data

Soil Type	Cement type	Cement contents (%)	Moulding dry unit weight (kN/m^3)	w (%)	Curing periods (days)
London clay	Early strength Portland cement	1, 3, 5 and 7	14.0, 15.0 and 16.0	30	7
Paraguay dispersive clay	Early strength Portland cement	3, 5 and 7	16.0, 17.5 and 19.0	13	3, 7 and 28
Botucatu Residual Soil	Early strength Portland cement	1, 2, 3, 5, and 7	17.5, 18.0 and 19.5	10	7
Red silty clay	Early strength Portland cement	3, 5, 7 and 9	14.0, 15.0 and 16.0	15 and 18	7
Organic soft clay	Early strength Portland cement	8.5 to 50	5.0, 6.0, 7.0 and 8.0	88 to 158	7
Silt	Early strength Portland cement	3, 5, 7 and 9	14.0, 15.0 and 16.0	17, 20 and 23	7
Gold tailings	Early strength Portland cement	3, 5 and 7	15.0, 16.0 and 17.0	17	7
Coal fly ash	Early strength Portland cement	2, 3, 4, 5, 7 and 9	11.0, 12.0 and 13.0	18	7

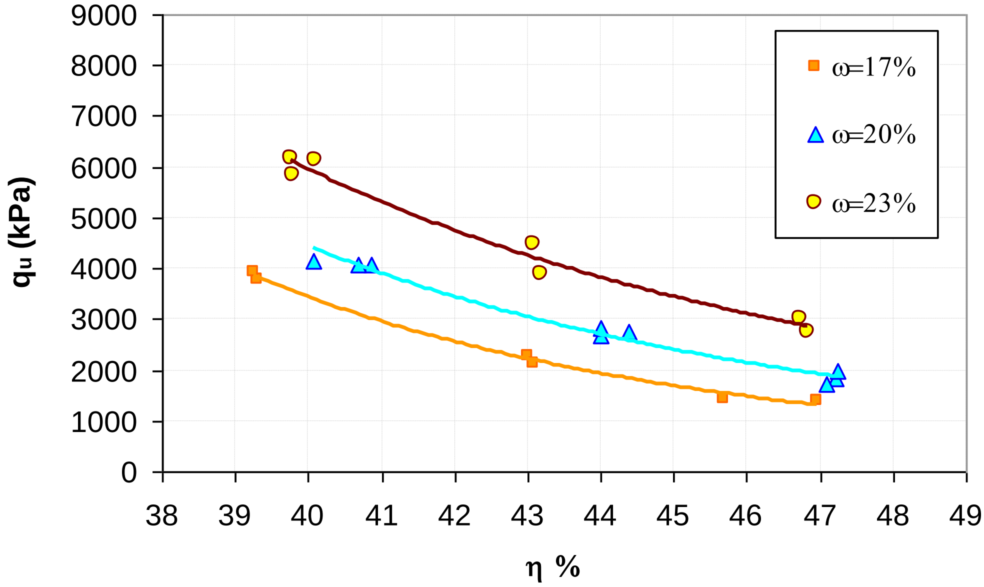
Table 3. Normalization data

Soil Type	Normalization Index (∇)	q_u (kPa) for Normalization	Coefficient of Determination (R^2)
London clay	$\eta/(C_{iv})^{0.28}=30$	1208.1	0.92
Paraguay dispersive clay	$\eta/(C_{iv})^{0.28}=30$	665.8, 882.8 and 1082.0 (respectively for 3, 7 and 28 days)	0.97, 0.95 and 0.97 (respectively for 3, 7 and 28 days)
Botucatu Residual Soil	$\eta/(C_{iv})^{0.28}=30$	630.1	0.98
Red silty clay	$\eta/(C_{iv})^{0.28}=30$	1190.7 and 1424.5 (respectively for w=15% and 18%)	0.94 and 0.92 (respectively for w=15% and 18%)
Organic soft clay	$\eta/(C_{iv})^{0.28}=30$	960.9	0.95
Silt	$\eta/(C_{iv})^{0.28}=30$	3021.0, 3920.2 and 4964.9 (respectively for w=17%, 20% and 23%)	0.85, 0.81 and 0.86 (respectively for w=17%, 20% and 23%)
Gold tailings	$\eta/(C_{iv})^{0.28}=29.0$	1817.4	0.97
Coal fly ash	$\eta/(C_{iv})^{0.28}=31.6$	3911.0	0.89

FIGURES



(a)



(b)

FIGURE 1: Unconfined compressive strength (q_u) with porosity (η) for silt with [a] C=3, 5, 7 and 9 %, water content of 20% and 7 days curing period and [b] considering C=7%, water contents of 17%, 20% and 23% and 7 days curing period.

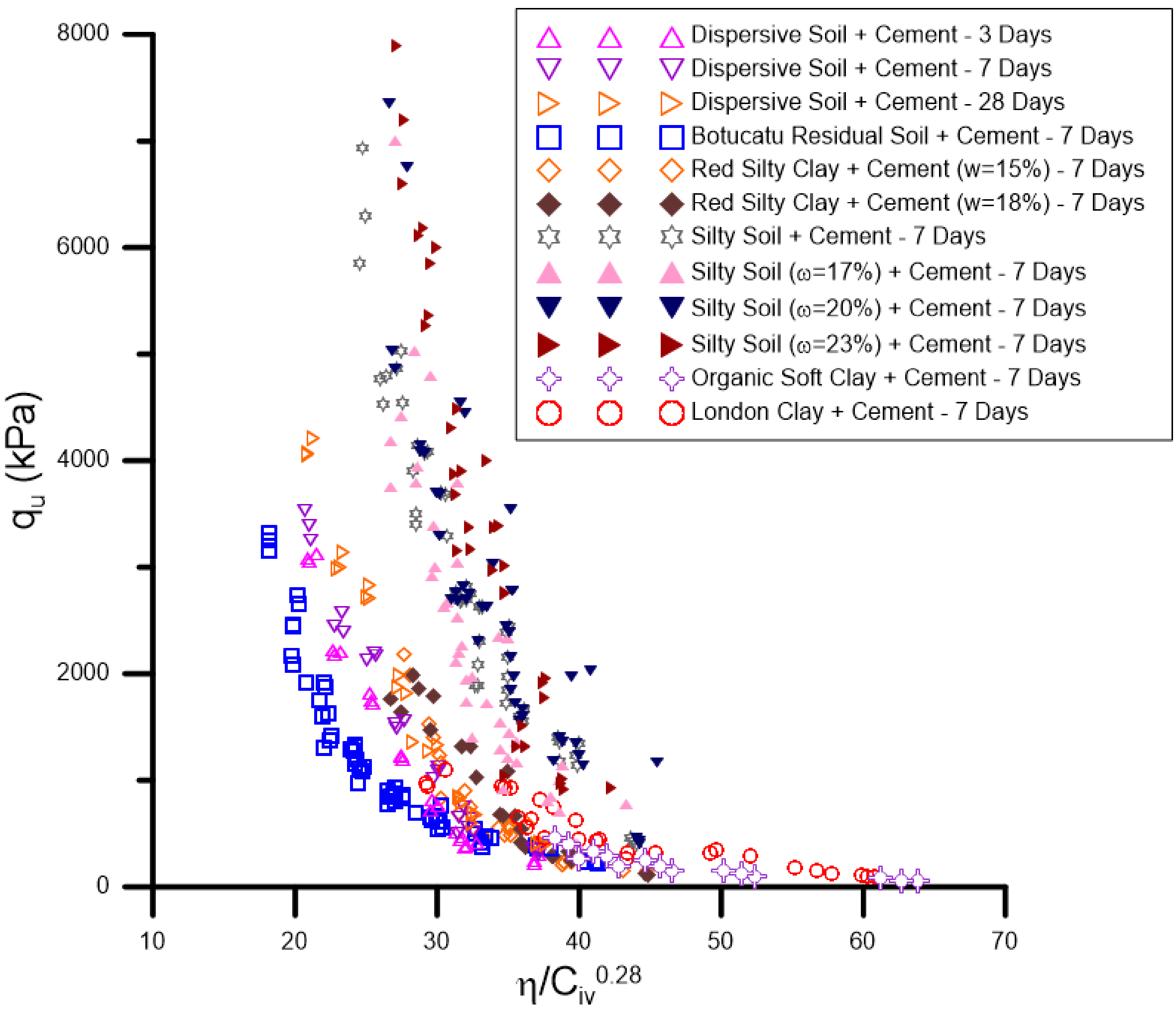


FIGURE 2: Variation of unconfined compressive strength (q_u) with adjusted porosity/cement ratio for all fine-grained soils studied and considering distinct curing periods (3, 7 and 28 days).

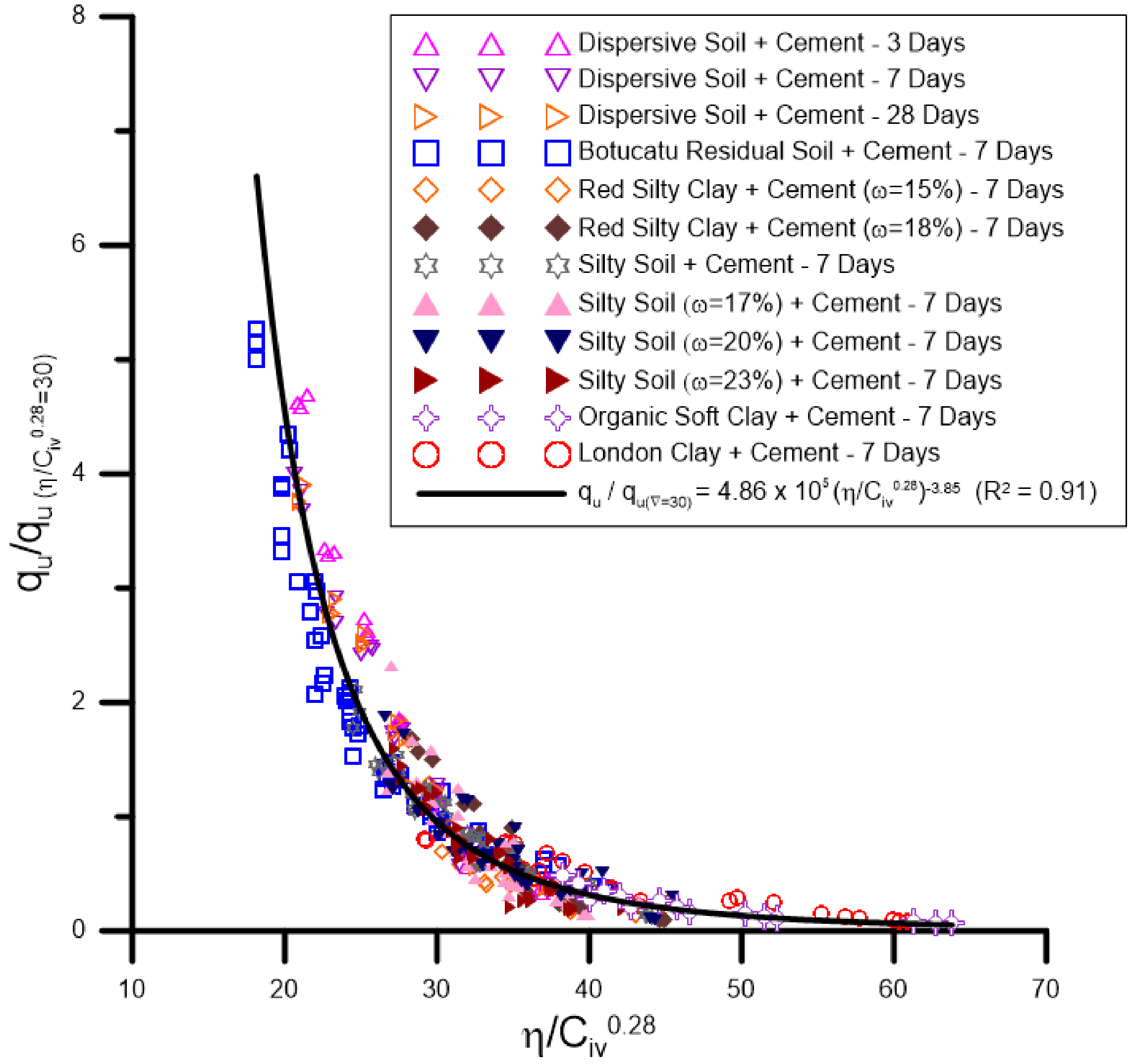
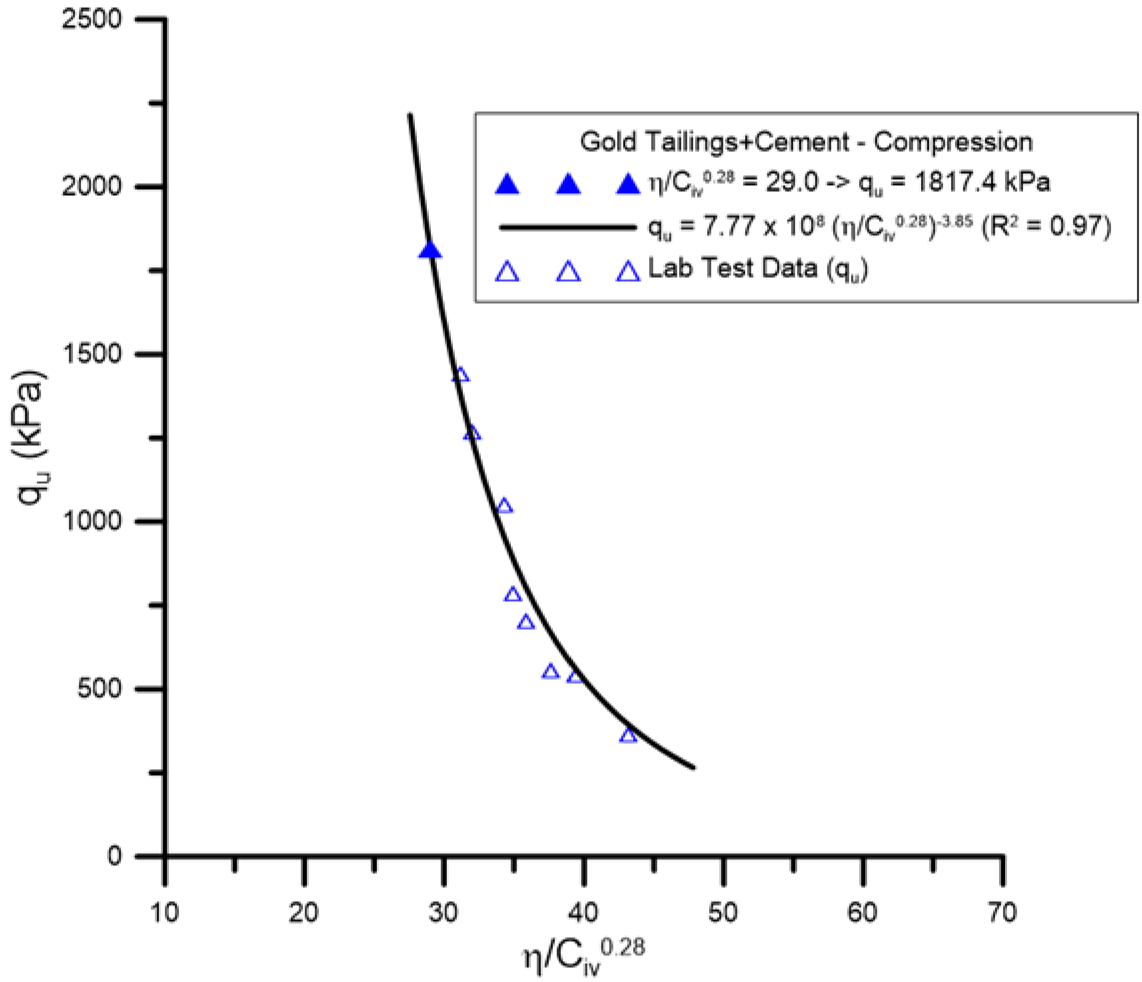
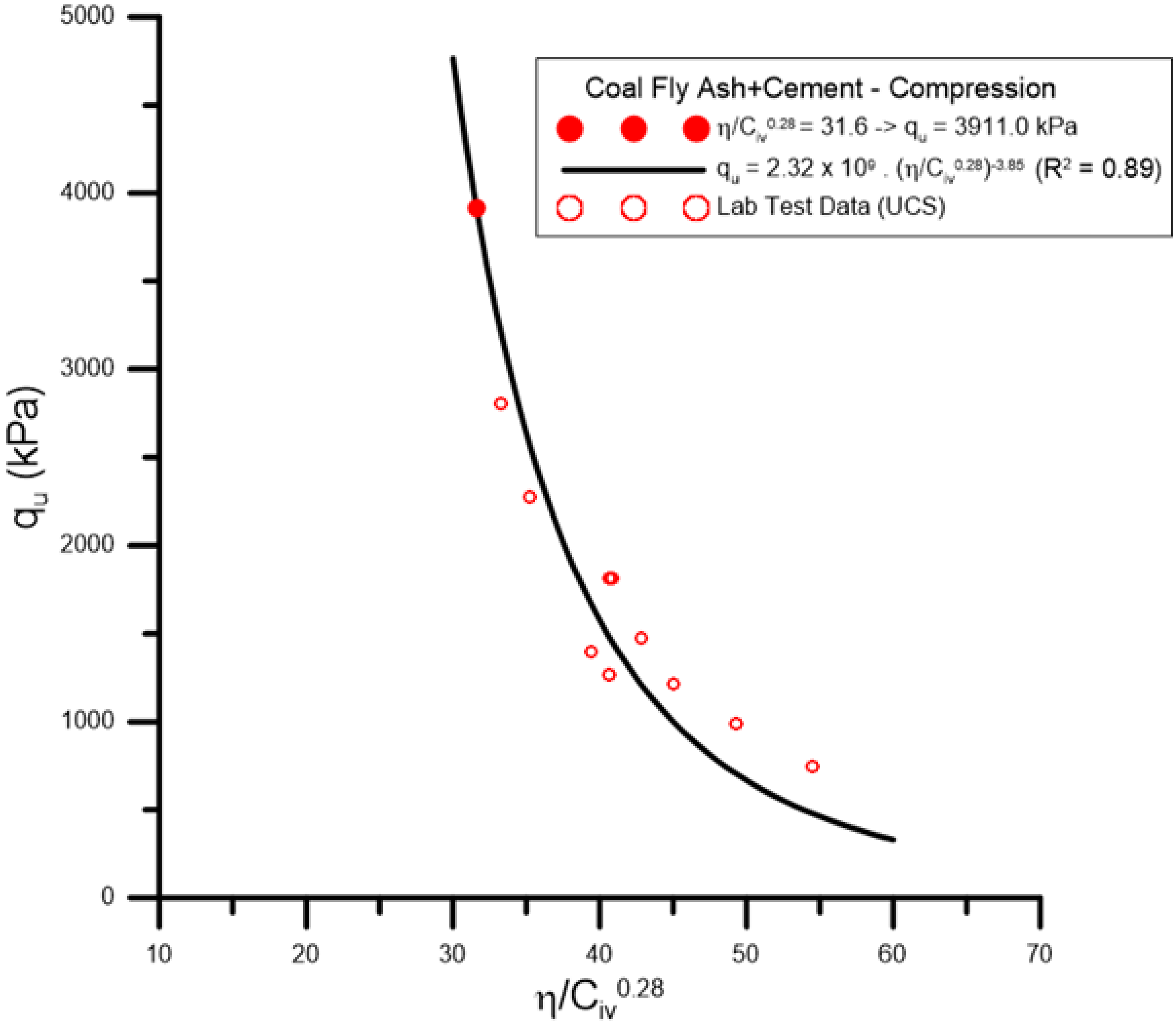


FIGURE 3: Normalisation of q_u (for the whole range of $\eta/C_{iv}^{0.28}$) with adjusted porosity/cement ratio for all fine-grained soils studied and considering distinct curing periods (3, 7 and 28 days).


Gold Tailings+Cement - Compression
η/C_iv^0.28 = 29.0 -> q_u = 1817.4 kPa
q_u = 7.77 x 10^8 (η/C_iv^0.28)^-3.85 (R² = 0.97)
Lab Test Data (q_u)
q_u (kPa)
η/C_iv^0.28
2500
2000
1500
1000
500
0
10
20
30
40
50
60
70

(a)



(b)

FIGURE 4: Curve obtained using Eq. (7) and lab-testing data for (a) gold tailings-Portland cement and (b) coal fly ash-Portland cement, both under a curing period of 7 days.

RESPONSE TO THE REVIEWERS COMMENTS

Ms. Ref. No.: SANDF-D-15-00366
Title: A Unique Relationship Determining Strength of Silty/Clayey Soils - Portland Cement Mixes
Journal: Soils and Foundations

1. GENERAL COMMENTS TO AUTHORS

This technical note aims to determine a unique relationship for predicting the unconfined compressive strength (q_u) of silty/clayey soil-Portland cement mixtures. Authors carried out unconfined compression tests on artificially cemented silty/clayey soil specimens with various properties: moisture content, porosity, cement content and curing period. Then, the values of q_u normalized by q_u of a specimen with a specific modified porosity/cement ratio $(\eta/(C_{iv})^{0.28})=30$ were plotted against a modified porosity/cement ratio. Authors conclude that the relationship between the normalized q_u and modified porosity/cement ratio is uniquely determined regardless of soil type, water and cement contents, and porosity, and the relationship can be expressed by a single equation proposed by Consoli *et al.* (2007) with a unique value of parameter B. These findings will be useful for the readership of the journal. However, although a uniqueness of the parameter B is emphasized in this note, the reviewers concerned that the B value may be influenced by soil type and a specific modified porosity/cement ratio (=30) employed. The section "Unique relationship establishing strength" needs to be modified to verify the uniqueness of B with its limitations. The manuscript needs substantial revisions listed below, to be accepted for publication.

All points raised by the reviewers were responded by the authors. Additional information regarding the parameter B was provided to support analysis.

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2. REVISIONS

- Technical items for which revision are compulsory

M1. p.5, line 134, "The value 0.28 was found to be the best fit exponent for all silty/clayey soils studied": According to Consoli et al. (2007), the value 0.28 provided the optimum fit for the relationship between unconfined compression strength and voids/cement ratio of the soil-cement mixture. However, they dealt with only one sandy soil. It is required to carefully explain the reason why this value is also applicable to silty/clayey soils with its physical meaning.

The following sentences were added to text to address the reviewer comment.

"The exponent value 0.28 was found to be the best-fit exponent for all silty/clayey soils studied herein. Previous empirical studies on clayey sand (Consoli et al. 2007), silty-clay and sandy-clay (Consoli et al. 2011), and silty sand (Rios 2011, Consoli et al. 2012) have shown that the exponent might slightly vary from 0.21 to 0.35, having an average value of 0.28 (adopted as the representative value in present research)."

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M2. Section "Unique relationship establishing strength":

- Fig 3: The authors should add some clarification on determination of a normalization index. The reviewer concerned that the B value is influenced by this index. Does $q_u(\eta/(C_{iv})^{0.28})$ have lower or upper limits? Why did the authors employ a $\eta/(C_{iv})^{0.28}$ of 41.7 for coal fly ash case? Why did the authors pick q_u at $\eta/(C_{iv})^{0.28}$ = 30 for Fig 3?. Does this approach generalize for other silty soils? Please explain this in more detail.

The work of Diambra et al. (2016) was used to support the description of the parameter B. Any value of $\eta/(C_{iv})^{0.28}$ inside of the studied range would work for normalization. Values of qu at $\eta/(C_{iv})^{0.28}$ around 30 were chosen once 30 exists for all silty-clayey soils – Portland cement results tested. Therefore, based on the experience obtained with the existing data, it is suggested the use of values nearby 30 (the authors now employ a $\eta/(C_{iv})^{0.28}$ of 31.6 for coal fly ash case).The authors understand this approach can be used for other silty soils.

The authors have improved section "Unique Relationship Establishing Strength" and added additional informational to explain this point in more detail.

- Equation 5: Why B = 3.85 for all values of $q_u(\eta/(C_{iv})^{0.28})$. Is this a practical value for any silty soils? Please explain this in more detail. The reviewer has some concerns on a unique relationship between the results for the various soils in Fig. 3. For example, when $\eta/(C_{iv})^{0.28}$ is less than 30, RBS (7 days) data lies below the proposed relationship while Dispersive Soil (3 days) data lies above the proposed relationship. Moreover it seems that London Clay data can be fitted by a linear relationship.

The authors have improved the text and added additional informational to explain this point in more detail. The work of Diambra et al. (2016) was used to support the description of the parameter B. A total of 342 specimens' strength results derived the parameter B value of 3.85. This value is quite similar to the theoretical value of 3.57 (as described in text). Thus the authors understand this value can generally be used for silty soils. It is possible to observe that the shape of the draw curve is quite similar to the trend shown by the lab points and that it represents *the average behavior of all mixtures with a global coefficient of determination R^2 of 0.91. When different mixtures are studied separately, the specific values of R^2 continue high(as shown in Table 3).*

- The writing lacks conciseness. This section needs to be revised to remove repetition and confusion in mathematical descriptions.

  Section was completely rewritten.

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M3. p.6, line 160, "It is important to recall that Eq. (5) is valid for any curing period" and CONCLUSIONS: The effect of curing time is investigated only on a dispersive soil. Thus, this conclusion needs to be re-written as a qualifying statement.

Conclusions were rewritten.

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- <u>Technical items for which revision are recommended</u>

<u>S1. p.5 line 124, "It can be seen...": According to previous studies (e.g. CDIT, (2002), The Deep Mixing Method, p.30), q_u decreases as the water content increases. It is recommended to explain the reason of the contradiction between the test results in this study and previous studies.</u>

Several authors (e.g. Horpibulsuk et al. 2003) have shown that a relationship exists between q_u and water/binder ratio (w/c - defined as the water mass divided by the cementitious material mass) for both soil–lime and soil–cement blends. Consoli et al. (2009a) has shown that this is only true in specimens in which the pores are water-filled, so that the water content would reflect the amount of voids. This is similar to what happens in Portland cement concrete, where the amount of water again reflects the amount of voids. Consoli et al. (2009a) has shown that when the voids are only partially filled by water such a relation is not accurate. In addition, the roles played by the porosity and by the water content are different. While water affects the strength by possibly changing the soil structure, porosity affects the strength by modifying the number of contact points among the soil particles. Therefore for the soil cement in the unsaturated state, as is usual in engineering practice, a relationship between porosity and cement content [porosity/cement ratio (η/C_{iv} - defined as the porosity divided by the volumetric cement content)] is more appropriate in the analysis and control of mechanical strength.
In cases where the pores are water-filled, increasing water content means increasing porosity. In cases when the voids are only partially filled by water, the structure that is formed depends on the soil moisture content (that is the present case).

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S2. The coefficient of determination is missing for the verification in Fig 4.

The coefficient of determination (R^2) was inserted in Fig. 4.

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- Items for which editorial revision are required

E1. p.3, line 59: "and Pantano Grande silt.." -> "and Pantano Grande silt."

Corrected as requested.

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E2. p.3, line 73: What does "r" mean?

It was a mistake, so it has been removed.

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E3. p.3, line 78: A unit weight of each blend (gamma s_s and gamma s_c) needs to be cited in NOTATION.

Added to NOTATION as requested.

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E4. p.5, line 113: "all tested silty/clayey soil" instead of "all tested sand"

Corrected as requested.

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E5. p.5, line 114 and Table 2: Table 2 might be misunderstood by readers. Since each specimen has its own porosity (η) and volumetric cement content (C_{iv}), the parameter $\eta/(C_{iv})^{0.28}$) must be specific to each specimen. Thus, an expression $\eta/(C_{iv})^{0.28}=30$ on Table 2 may confuse readers. As Table 2 is explained in chapter "EXPERIMENTAL PROGRAM", it needs to concentrate on the molding data. Besides, it seems to be better to move the normalization ones to chapter "RESULTS".

Table 2 was divided and another table was created (Table 3) to avoid misunderstanding. Table 2 now is explained in chapter "Experimental program" and concentrates in the molding data. Table 3 presents the normalization data and is explained in chapter "Results".

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E6. p.6, line 146: Fig. 5 cannot be found in the manuscript.

It should be Fig. 3. It was corrected in the manuscript.

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E7. p.6, line 154: "B = 3.85" instead of "C = 3.85"

Corrected as requested.

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E8. p.7, line 171: A power of "-3.85" is redundant.

Power "-3.85" was removed as requested.

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E9. p.10, NOTATION: A notation "t" cannot be found in the manuscript.

Notation "t" was removed.
